Double-slit experiment at the femtometer scale with ALICE

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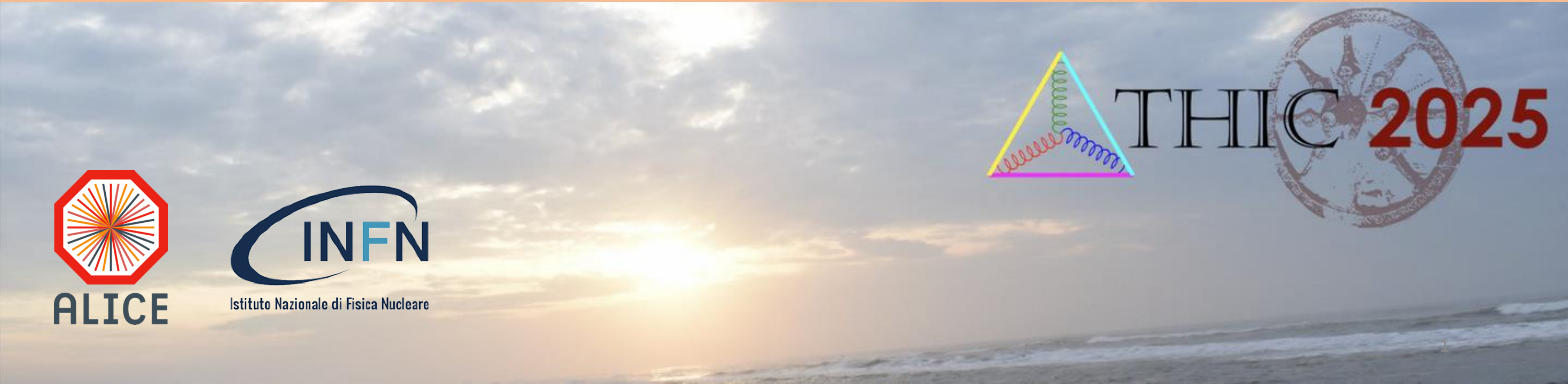
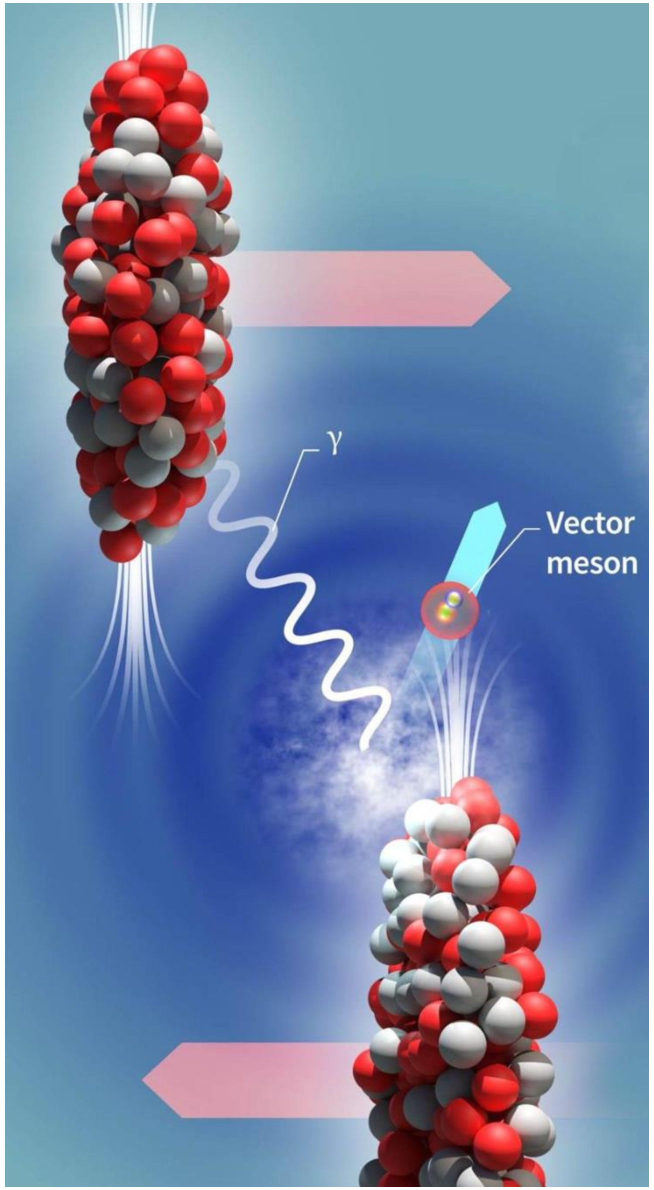


Ultra-peripheral collisions

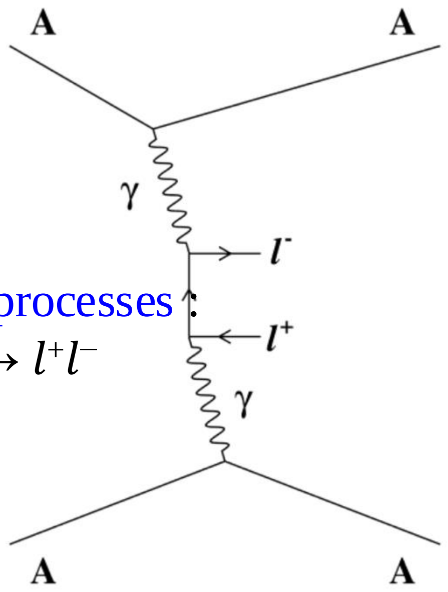


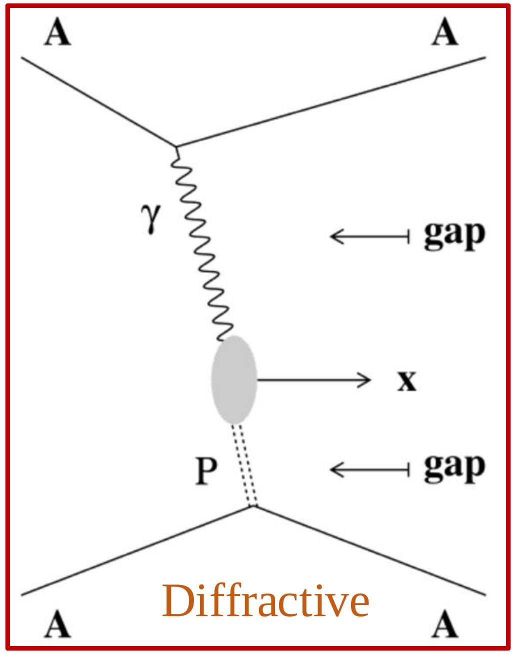
b > 2R

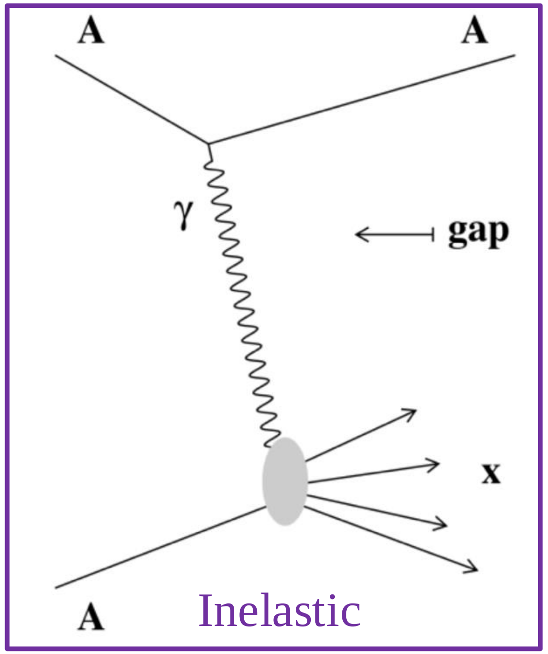
- **Ultra-peripheral collisions (UPCs):** **$b > R_1+R_2$**
- **Electromagnetic fields:**
  - Proportional to Z^2
  - Treated as quasi-real photon fluxes
- Electromagnetic dissociation cross section ~ 30 times greater than hadronic
- Hadronic interactions are short range: highly suppressed in UPCs
  - UPCs allow us to study the photon-induced reactions, such as purely EM processes, but also photon-nuclear reactions

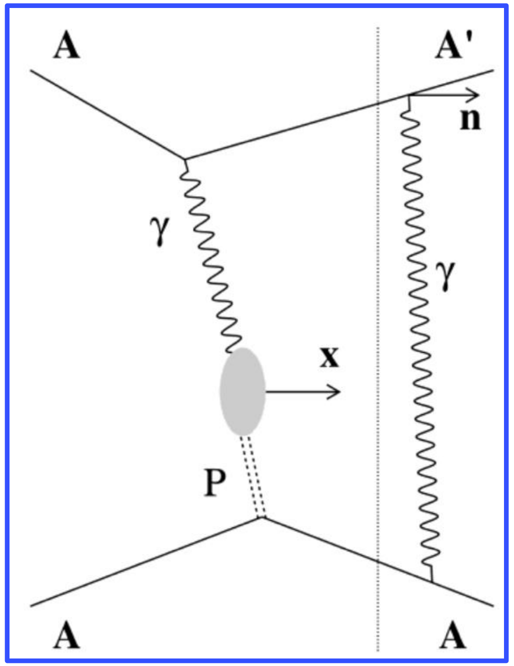
Processes in UPCs

Pure EM processes :
$\gamma\gamma \rightarrow l^{+}l^{-}$









Photon-induced reactions: pure EM processes or γ-nucleus reactions

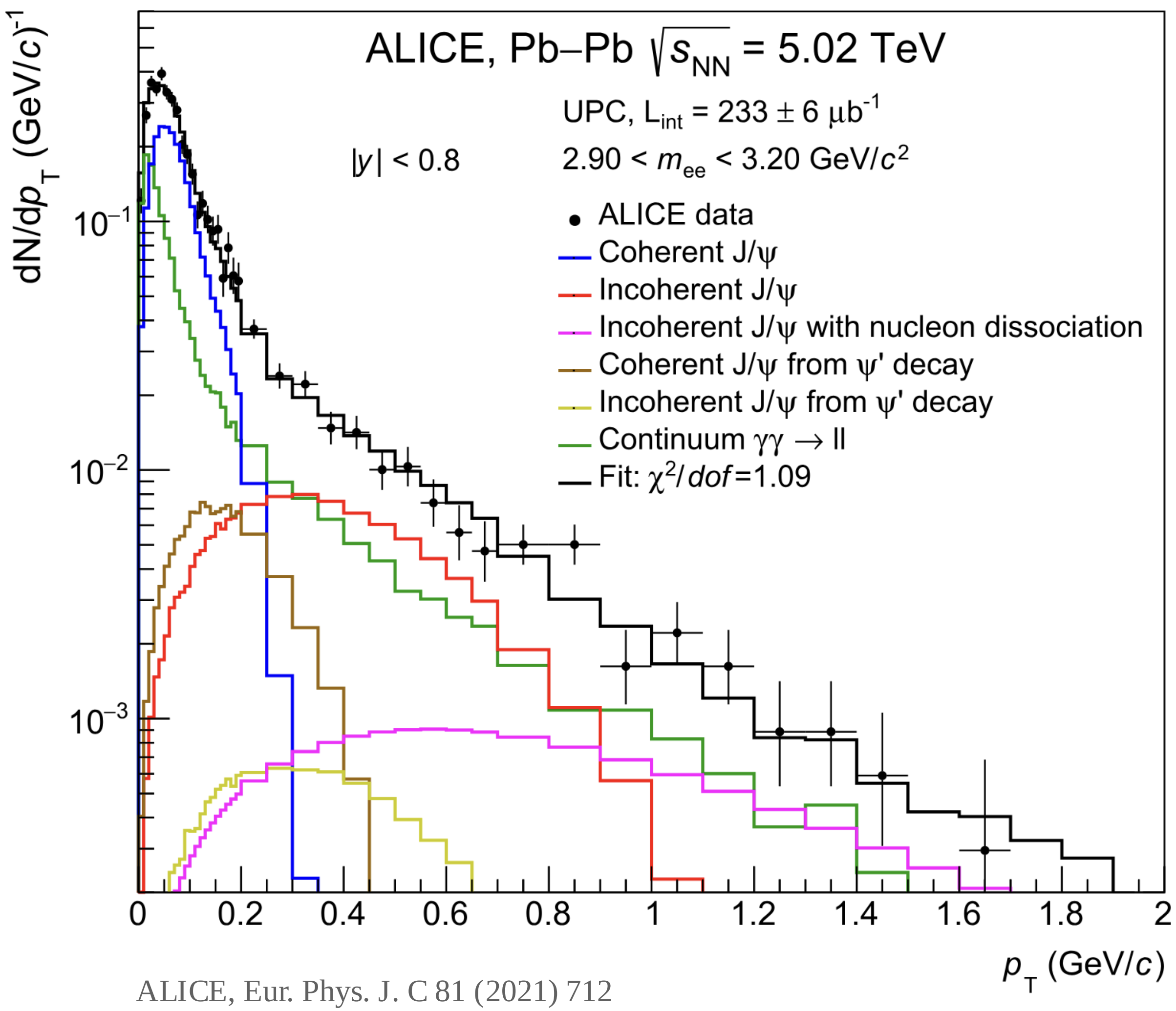
- γ-nucleus reactions:

    Diffractive: Interaction without color exchange → 2 rapidity gaps

    Inelastic: Color exchange→ rapidity gap only in the photon side

- Intense EM field: possible to have multi-photon exchange, that may lead to electromagnetic dissociation (EMD) processes that cause neutron emission at beam rapidity

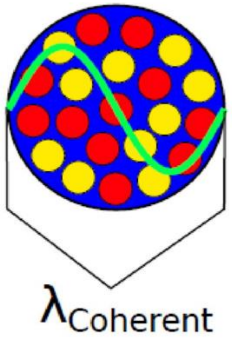
Coherent and incoherent photoproduction



ALICE, Eur. Phys. J. C 81 (2021) 712

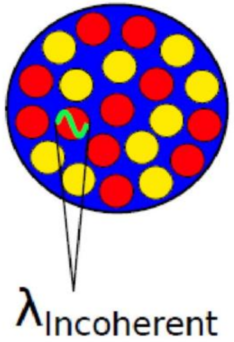
Coherent:

- The photon interacts with the nucleus as a whole and the nucleus remains intact
- $\langle p_T \rangle \sim 1/R_{Pb} \sim 60$ MeV/c
- Exclusive process

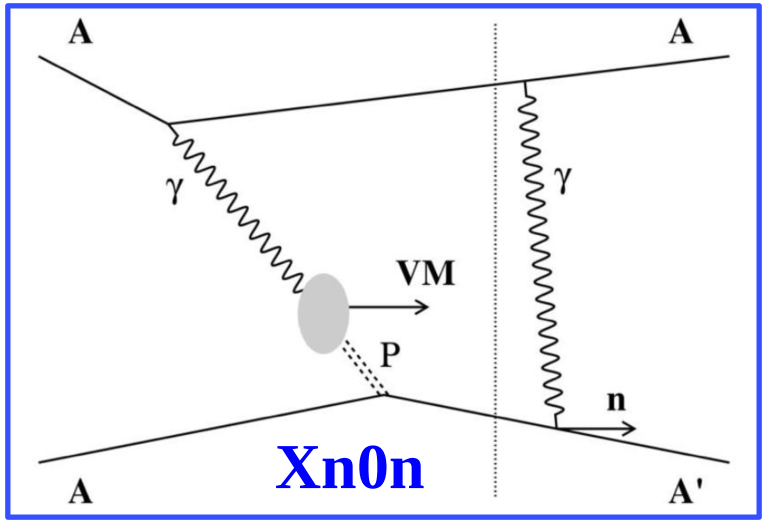


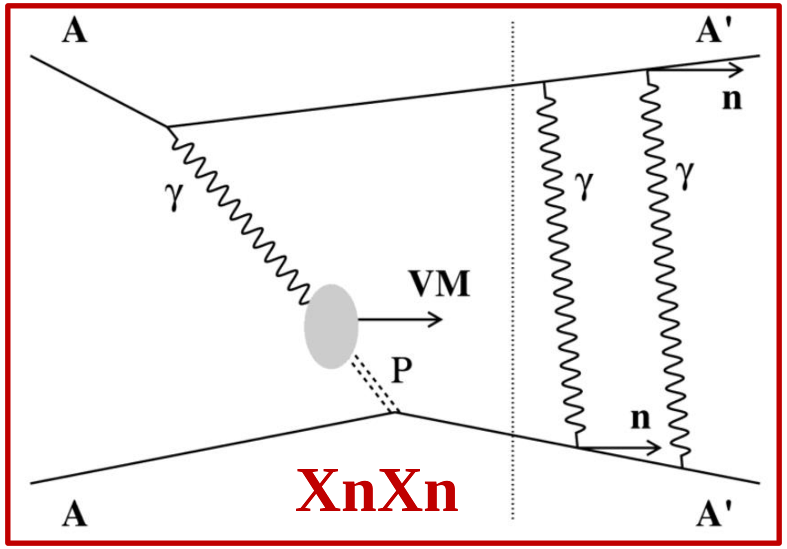
Incoherent:

- The photon interacts with only one nucleon
- The nucleus usually breaks up
- $\langle p_T \rangle \sim 1/R_p \sim 450$ MeV/c



Electromagnetic dissociation (EMD)





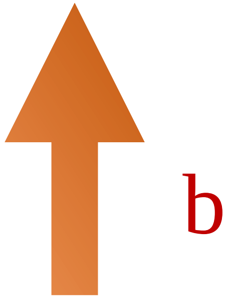
- Vector meson photoproduction can occur with independent EMD processes
- EMD needs the exchange of energetic photons

  → The probability of finding energetic photons decreases as the impact parameter increases
- EMD processes can be used to select different impact parameter ranges in UPCs
- EMD classes from large to small *b*:

  0n0n: no EMD

  Xn0n: EMD of one of the nuclei

  XnXn: Both nuclei undergo EMD

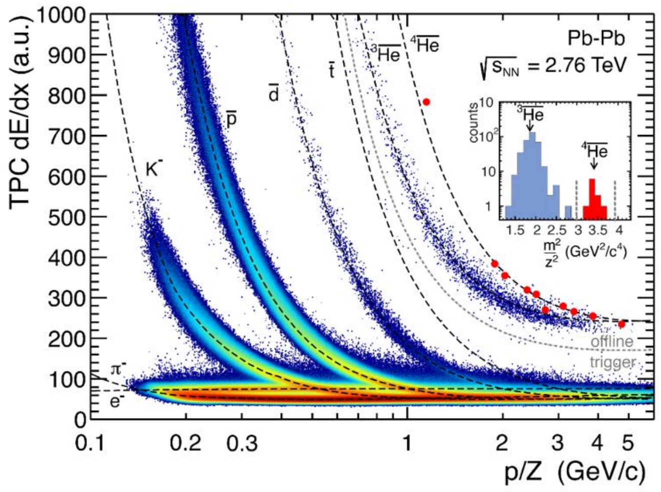


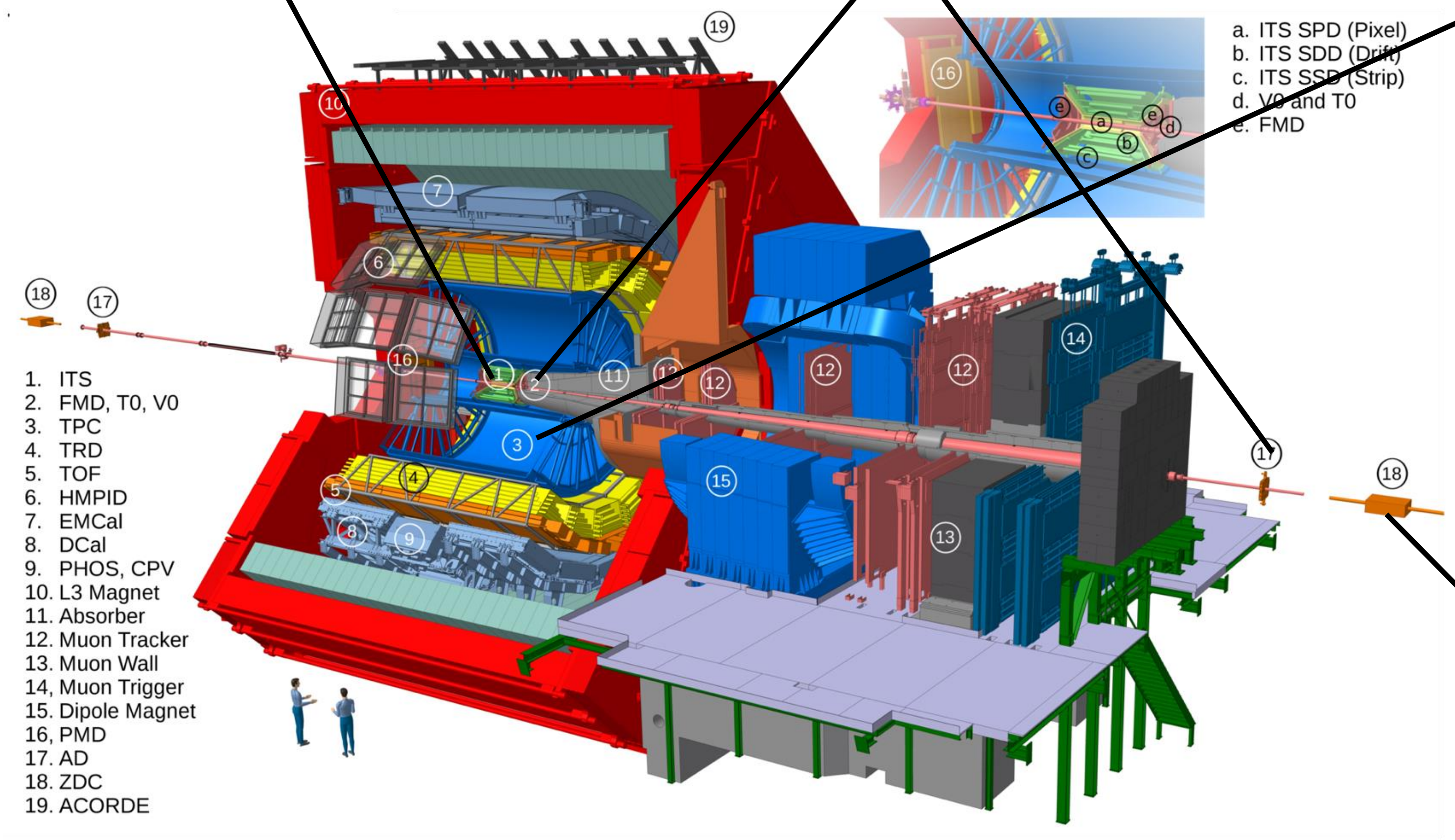
ALICE in Run 2

ITS (silicon): 6 layers of silicon trackers. The 2 innermost layers are also used for triggering

AD/V0: Arrays of scintillators at forward rapidity. Ensure the presence of large rapidity gaps used for triggering

TPC: Tracking and PID through d*E*/dx

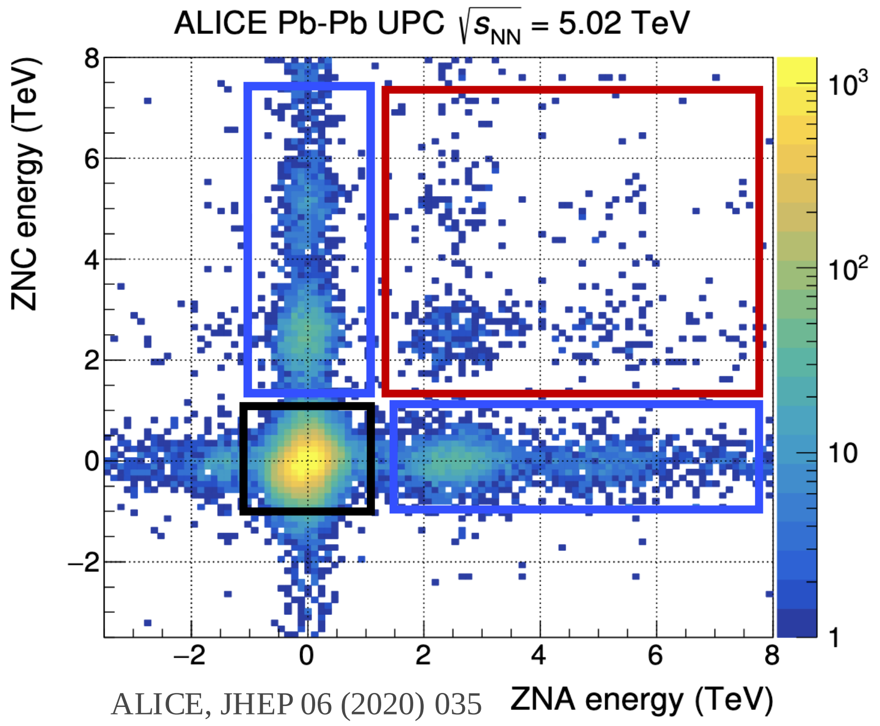




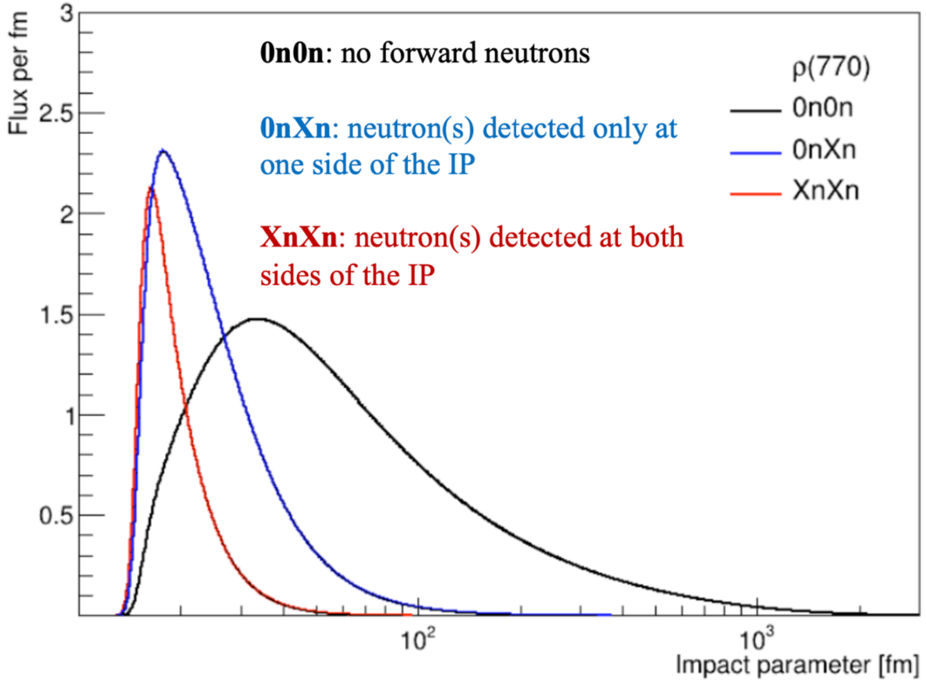
ZDC: Sampling spaghetti calorimeters. Used to detect forward neutrons and protons

Impact parameter selection in UPCs

- We classify events in different EMD classes using neutron detection in the ZDCs
- ALICE measured the cross section for neutron emission at beam rapidity in Pb-Pb UPCs and well reproduced by MC models
- Impact parameter distributions in different EMD classes in coherent ρ^0 photoproduction, according to the $\mathbf{n^0{}_0n}$ MC

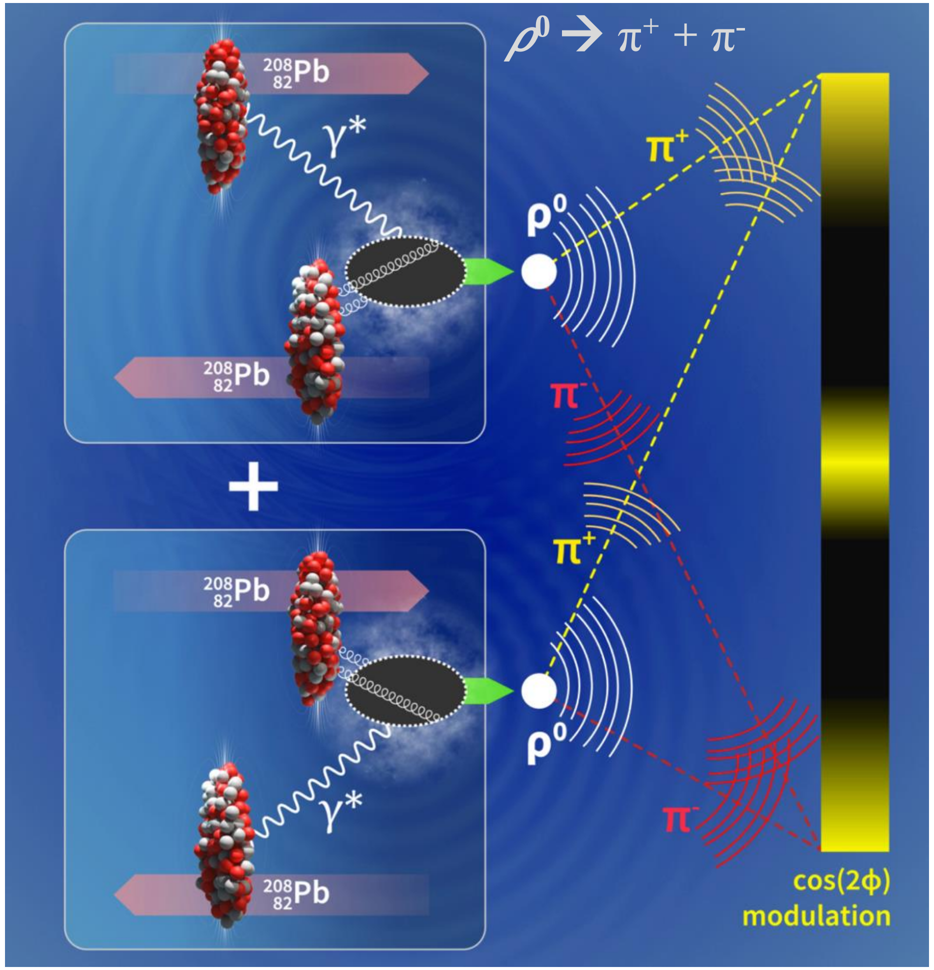


ALICE, JHEP 06 (2020) 035



EMD class	Median *b* from $\mathbf{n^0{}_0n}$
0n0n	49 fm
Xn0n	23 fm
XnXn	18 fm

Azimuthal anisotropy in coherent ρ^0 photoproduction



Each nucleus can act as the source of the photon or as the target in the interaction

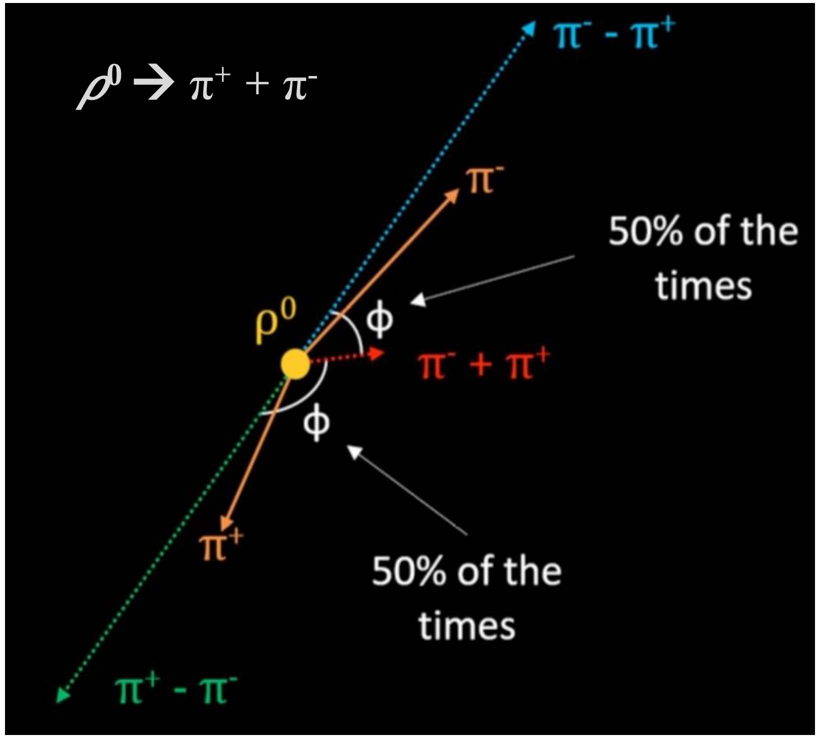
→ two indistinguishable amplitudes contribute to the cross-section

Interference between the amplitudes:

$$\sigma(p_{\mathrm{T}}, b, y=0) = \left| \; A(p_{\mathrm{T}}, b) - A(p_{\mathrm{T}}, b) \; e^{i\,\vec{p}\cdot\vec{b}} \; \right|^2$$

- Correlation between ρ^0 momentum and polarization (aligned along *b*) → preserves the anisotropy!
- The decay products are emitted in an entangled state, and the interference depends on observing the complete final state

What we measure in ALICE



φ = azimuth angle between p⁺ and p⁻

$p_T\pm = p_{T,\pi1} \pm p_{T,\pi2}$

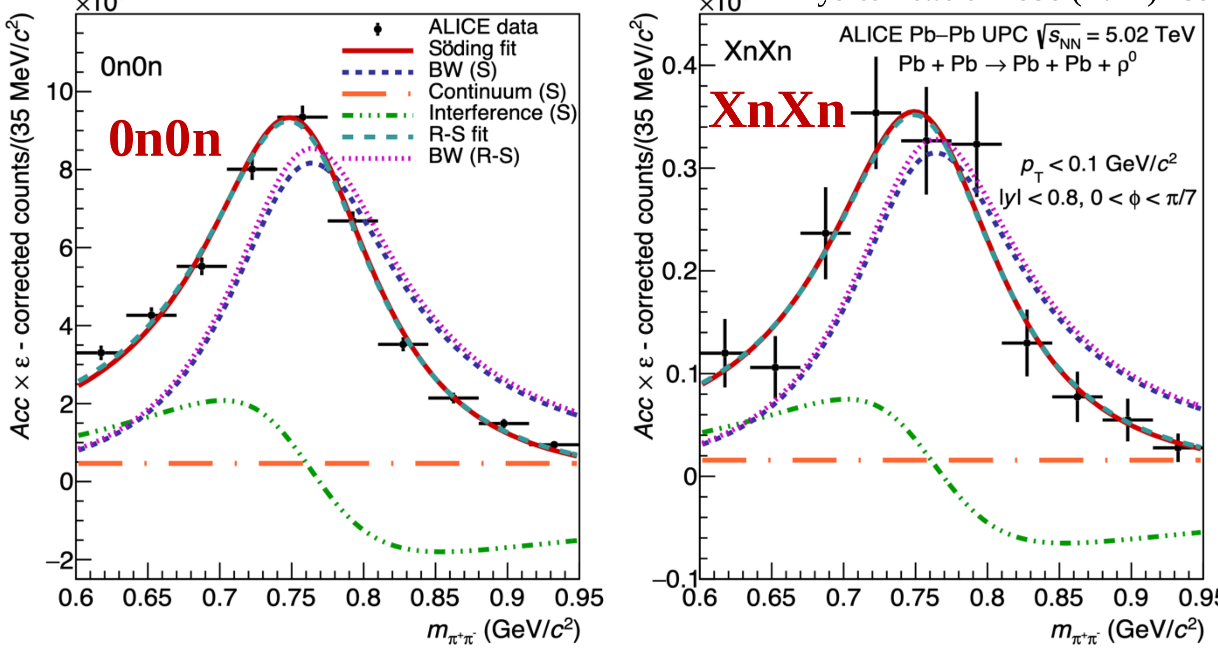
$p_{T,\pi1}$ ($p_{T,\pi2}$) = transverse momentum of the track randomly assigned to the positive and negative tracks

Söding model (Fit to invariant mass spectra):

The $\rho 0$ (resonant pion pair production) + continuum +interference between the two

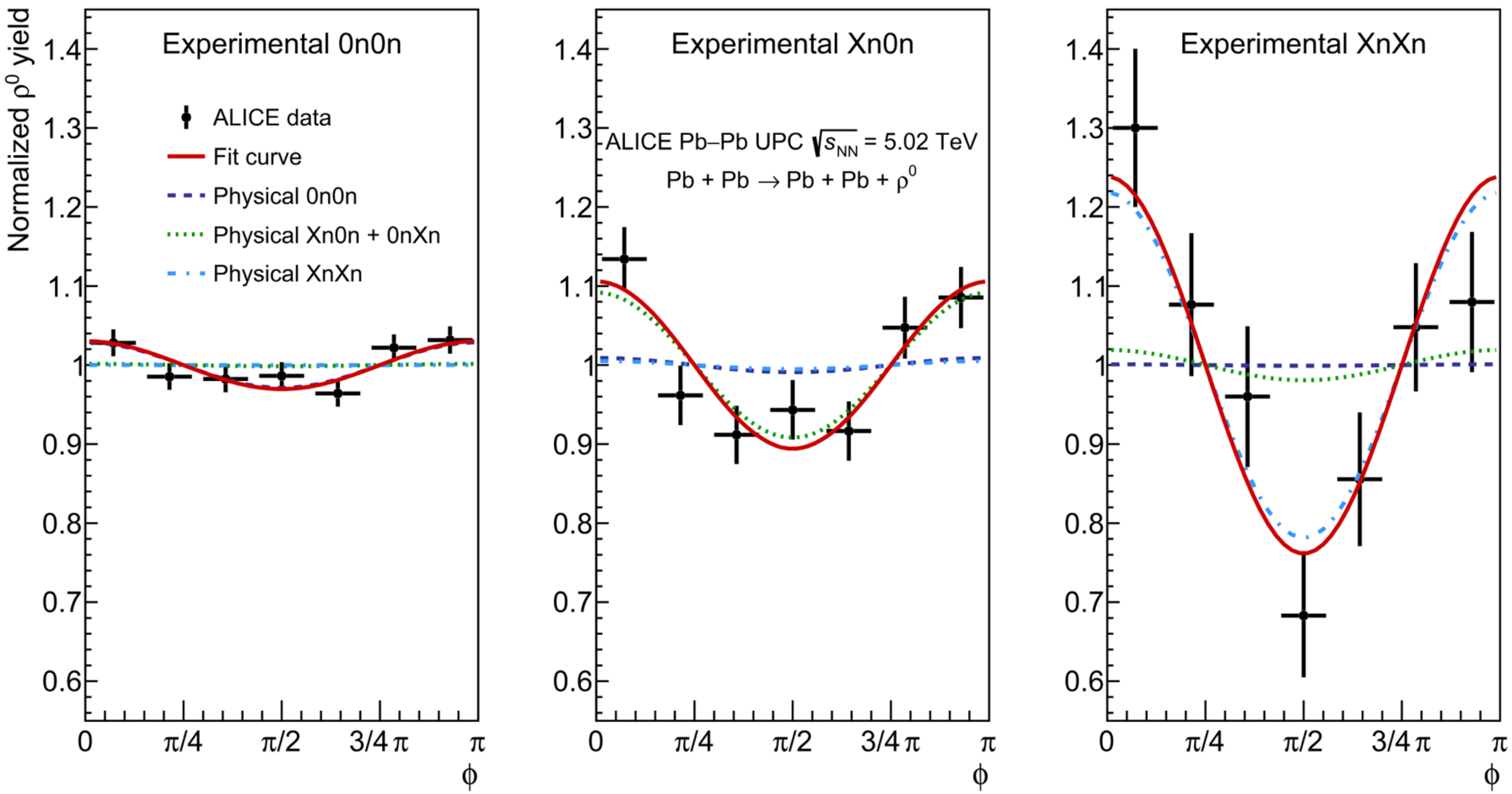
$$\frac{d\sigma}{dm_{\pi\pi}} = \left|A\, BW_{\rho} + B\right|^2 + M(m_{\pi\pi})$$

Physics Letters B 858 (2024) 139017



Example of the fit to the invariant mass distribution in a specific ϕ range

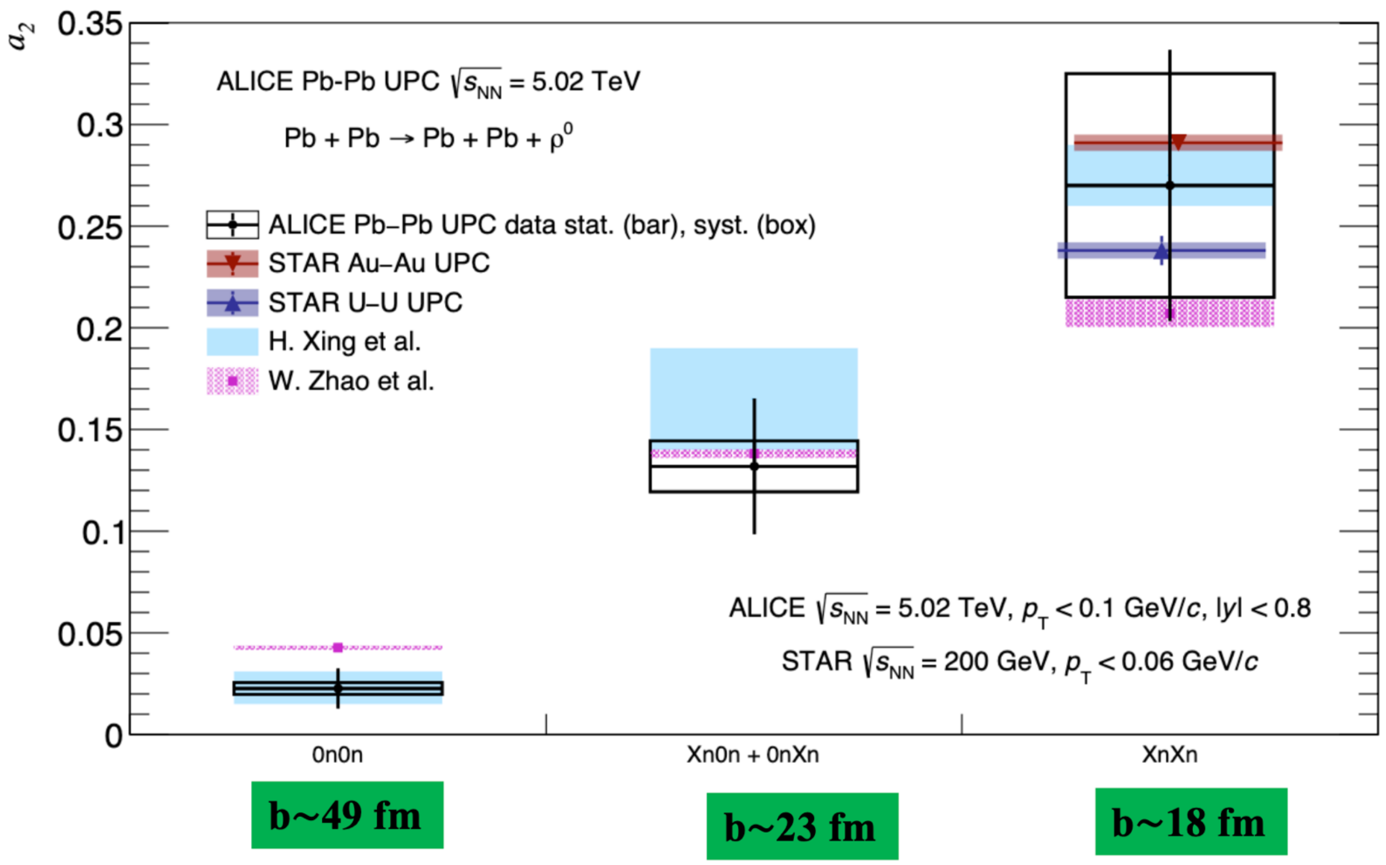
Asymmetry extraction



- Example of one of the fits to extract the amplitude of the modulation
- The different components of the modulation in each class due to migrations are shown
- The modulation strongly increases as b decreases

b

Result: Azimuthal anisotropy



- First measurement of the azimuthal anisotropy of the coherently photoproduced ρ^0 yield as a function of the impact parameter (b)
- The modulation strength strongly increases as *b* decreases → **XnXn > Xn0n > 0n0n**
- Compatible with predictions from both theoretical models[3, 4]
- XnXn amplitude compatible with STAR results for Au-Au and U-U collisions at lower energy

[1] Physics Letters B 858 (2024) 139017
[2] Sci. Adv. 9 (2023) eabq3903
[3] Xing et al., JHEP 10 (2020) 064
[4] Zhao et al., PRC 109 (2024) 024908

Summary and outlook

- First measurement of the angular anisotropy in the decay of coherently photoproduced $\boldsymbol{\rho 0}$ as a function of the impact parameter
- This experiment can be seen as a double slit experiment at fm scale, with b acting as the distance between the openings
- The strength of the anisotropy varies by one order of magnitude from the largest to the small impact-parameter event class

ALICE in Run 3:

- Constrain models with more differential studies of the interference at fm scale
- ALICE is taking data in continuous readout mode
- New upgraded detectors, Muon Forward Tracker (MFT) and Fast Interaction Trigger (FIT), will be used to select UPC events with a veto at forward rapidity
- In Run 3 + 4 we expect order(s) of magnitude more events wrt Run 2

$\rho^0 \rightarrow \pi^+\pi^-$ at midrapidity: 5.5 B expected as compared to ~ 57 k in Run 2

$J/\psi \rightarrow \mu+\mu-$ at midrapidity: 1.1 M expected as compared to ~ 3.1 k in Run 2

Thank you for your attention!!!

Back-up

Accounting for migration across EMD classes

- To extract the amplitude of the **anisotropy** we need to **fit the distribution of the normalized ρ^0 yields as a function of ϕ** in each neutron emission class.
- We are looking for a $\cos(2\phi)$ modulation with b-dependent amplitude, and $b \leftrightarrow$ neutron emission classes
- We need to **account for migrations across neutron classes**, due to ZDC efficiency for neutrons and pile-up

$$\begin{pmatrix} n_{\rho\,\mathrm{0n0n}} \\ n_{\rho\,\mathrm{Xn0n}} \\ n_{\rho\,\mathrm{XnXn}} \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} + \begin{pmatrix} w_{\mathrm{0n0n}\to\mathrm{0n0n}} & w_{\mathrm{Xn0n}\to\mathrm{0n0n}} & w_{\mathrm{XnXn}\to\mathrm{0n0n}} \\ w_{\mathrm{0n0n}\to\mathrm{Xn0n}} & w_{\mathrm{Xn0n}\to\mathrm{Xn0n}} & w_{\mathrm{XnXn}\to\mathrm{Xn0n}} \\ w_{\mathrm{0n0n}\to\mathrm{XnXn}} & w_{\mathrm{Xn0n}\to\mathrm{XnXn}} & w_{\mathrm{XnXn}\to\mathrm{XnXn}} \end{pmatrix} \begin{pmatrix} a_{2\,\mathrm{0n0n}} \\ a_{2\,\mathrm{Xn0n}} \\ a_{2\,\mathrm{XnXn}} \end{pmatrix} \cos(2\phi)$$

Normalized ρ^0 yield

$w_{Y\to Z}$ = contribution of the yield in the physical class Y to the yield in the experimental class Z. Computed from measured cross-section ratios and migration probabilities.

a_2 = true amplitudes of the modulation